ELSEVIER

Industrial Crops and Products 5 (1996) 53–63

INDUSTRIAL CROPS AND PRODUCTS
AN INTERNATIONAL JOURNAL

Collection and evaluation of new *Lesquerella* and *Physaria* germplasm

D.A. Dierig [a,*], A.E. Thompson [a], J.P. Rebman [a], R. Kleiman [b], B.S. Phillips [b]

[a] *USDA, Agricultural Research Service, U.S. Water Conservation Laboratory, Phoenix, AZ 85040-8832, USA*
[b] *USDA, Agricultural Research Service, Northern Center for Agricultural Utilization Research, Peoria, IL 61604, USA*

Received 4 April 1995; accepted 17 November 1995

Abstract

Lesquerella and the closely related genus *Physaria* are prime candidates as a new, alternative source of hydroxy fatty acids (HFA) for industrial uses. At present, castor oil is the only natural source of these HFA for commerce. To expand the germplasm base of these taxa for our breeding program and the National Germplasm System (NPGS), we collected species from a wide geographic region in the United States. In 1993, 44 accessions of *Lesquerella fendleri,* 38 accessions from nine other *Lesquerella* species, and three accessions of two different *Physaria* species were obtained. In 1994, 41 additional accessions of *L. fendleri* and 51 accessions of ten other *Lesquerella* species were collected. A total of 20 different species of *Lesquerella* and two *Physaria* species were collected over the two years. Oil characteristics and seed size of eight of these *Lesquerella* and one *Physaria* species have not previously been reported. Twelve of these taxa have not been available in the NPGS. Populations of *L. fendleri* collected in Arizona had higher seed-weights than those collected from Texas and New Mexico. Some of the new accessions had seed-weights higher than germplasm presently in the USDA–ARS breeding program. Diverse growth habits were found in populations from all three states. We believe that other species of *Lesquerella* and *Physaria* could later be developed as a source of HFA in regions other than the arid southwestern United States. Accessions of *Lesquerella douglasii* had the same or higher seed-oil content than *L. fendleri* and also higher seed yields. Two accessions of *Physaria newberryi* had seed-weights that ranged between 4.5 and 6.2 g/1000 seeds compared to that of 0.25 to 1.1 g/1000 seeds for *L. fendleri.* Seed-oil contents of *P. newberryi* averaged 30.8% compared to 23.8% for *L. fendleri.* Preliminary seed increase and evaluation of oil content and composition were completed on 14 *L. fendleri* populations from the 1993 collection under field conditions in Phoenix, Arizona. Accessions were compared to the original populations collected in 1993 and 1994 for growth habit, seed size, and seed-oil content and quality.

Keywords: Industrial oilseed; New crops; Hydroxy fatty acid; Plant exploration

1. Introduction

Seed-oils of *Lesquerella* and *Physaria* species are good sources of three types of hydroxy fatty acids (HFA), lesquerolic, densipolic, and auricolic. Along with other potential uses, HFA may serve as a replacement for castor oil. Lesquerolic acid has a C_{20} chain length compared to the C_{18} of ricinoleic acid from castor. The chain length and chemical reactivity of an HFA determines the value of the oil for industrial purposes (Roetheli et al., 1991). Potential uses of the oil include chemical feedstocks for production of plastics, lubricants, protective coatings, surfactants, cosmetics, and pharmaceuticals (Dierig et al., 1993).

* Corresponding author.

SSDI 0926-6690(95)00052-6

The seed meal has a high protein content and good potential as a feed supplement for ruminants (Miller et al., 1962). The seed coat of lesquerella contains a water-soluble gum with possible uses in cosmetics, plasticizers, coatings, food thickening agents, and crude oil recovery (Abbott et al., 1994).

There are 83 known *Lesquerella* species native to North America (Rollins, 1993b). Approximately half of these have unique and desirable characteristics that could be exploited for breeding purposes either in the incorporation of traits into *Lesquerella fendleri*, or for developing other sources of HFA for different geographical areas (Rollins, 1993a). Of 23 different *Lesquerella* species evaluated, *L. fendleri* has the highest agronomic potential for the southwestern United States. (Thompson and Dierig, 1994). *L. fendleri* is native to the southwestern United States., including the states of Arizona, New Mexico, Texas, and parts of southeastern Utah, and throughout Mexico. Only a narrow germplasm base has been utilized in the domestication of *L. fendleri* (Thompson and Dierig, 1994).

An active domestication and commercialization effort is being conducted by USDA-ARS at the U.S. Water Conservation Laboratory (USWCL), and by other government agencies, private industries, and universities, to develop *Lesquerella* as an industrial oilseed crop for lesquerolic acid production. Currently, 27 accessions of *L. fendleri* are in the National Plant Germplasm System (NPGS), most of which are from the southwestern United States. An additional 69 accessions of 21 *Lesquerella* species, with only one accession of a *Physaria* species are available (Thompson et al., 1992). Many of the species in the NPGS collection have only one or two accessions and do not adequately represent the genetic diversity available in the known taxa of the genus *Lesquerella*. Unfortunately, these southwestern species are grossly under-represented relative to the number and geographic distribution of the native populations.

Considerable genetic variations for seed-oil and agronomic characteristics exist in natural populations both within and among species of *Lesquerella* (Rollins and Shaw, 1973). This genetic variation could be helpful for the domestication and commercialization efforts now in progress. The closely related species of the genus *Physaria* also contains HFA. Little information is available with regard to the genetic diversity and potential of this genus. Nearly 20 *Physaria* species are known to occur in North America (Rollins, 1981, 1993b).

The purpose of this paper is to characterize the new additions to the *Lesquerella* and *Physaria* germplasm collections made in 1993 and 1994 and to discuss the initial evaluation of some of these germplasm.

2. Materials and methods

2.1. Collections

A database describing locality, collection data, time of flowering, and seed-set was compiled from existing specimens in several herbaria. This database was used for mapping the route of each collection trip. We began the collection in May 1993, concentrating primarily on *L. fendleri* throughout its natural habitat covering Arizona and New Mexico. Other available species of *Lesquerella* and *Physaria* occurring within this geographical area were also collected. In 1994, collections were made throughout Texas and Washington. Two trips were made to the collection sites. The first, to locate and identify the flowering plants (February–April) and a second return trip to collect mature seeds (April–June).

Geographical locality information for each population, such as state, county, nearest town, and road mileage marker were recorded as were latitude, longitude, and elevation from a Trimble Navigation Basic Plus[1], Global Positioning System (GPS). The GPS data were reported according to a WGS-84 map datum. A general description of the population habitat and the vegetation associated with the materials collected were recorded.

When available, flower buds were collected for meiotic chromosome number determinations. Flower buds were placed in Farmer's solution (three parts ethanol, one part glacial acetic acid) and stored in an ice chest while in the field. Buds were transferred and stored in 70% ethanol after 24 hours. Young

[1] Mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture, and does not imply its approval to the exclusion of other products that may be suitable.

anthers were extracted from the buds, and chromosome smears were prepared using the standard acetocarmine squash technique.

At least three individual whole *Lesquerella* plants were collected, pressed and dried for herbarium deposition as a voucher of each accession number. After species identification, one set of these specimens was deposited in the United States, National Arboretum Herbarium, Washington, DC. A second set was also deposited at Arizona State University, ASU Herbarium, and a third set at The Harvard University, Gray Herbarium. Dr. Reed Rollins, Emeritus Professor, Harvard University, verified species identifications.

2.2. Evaluations

Total seed-oil content was measured using a calibrated Bruker PC120 Pulsed NMR analyzer and oil composition on the Hewlett-Packard 5890 gas chromatograph. For the fatty acid analysis, the oil was first transesterified. This method consisted of first placing 25 seeds in a 1.5-dram screw-capped vial, wetted with hexane, then shattering them with a stainless steed rod. Approximately 1 ml of 1.5% sodium in methanol was added to the shattered seeds, the vial capped, and shaken vigorously, allowed to stand for a minimum of 10 min, and then treated with about 0.5 ml of 1%-NaCl solution. One milliliter of hexane was then added and the contents shaken vigorously. After allowing the layers to separate, the hexane layer was withdrawn from the top and transferred into a separate, clean vial. The combined hexane extracts were used for fatty acid analysis by gas chromatography. A 25-m 25QC3/BPX70-0.25 column (SGE, Victoria, Australia), with temperature programmed from 125° to 245°C at 3°C/min was used for the analysis. Identification of components was performed using Equivalent Chain Lengths and by comparisons with known standards.

Total seed-oil content analysis required a minimum sample size of two grams. In many cases, there was not enough available seed of an accession for this. The accessions in Tables 2, 3, and 4 having NA, data not available, in the column for oil (%) was due to limited amounts of seed for analysis.

The means of the 1000 seed-weight, oil content, and lesquerolic acid content of seeds of *L. fendleri* from native populations collected in Arizona (1993), New Mexico (1993), and Texas (1994) were compared using a t statistic (Table 2). Populations from Arizona were statistically compared to both populations from New Mexico and Texas, and also New Mexico to Texas. The analyses were performed using a t-test procedure program of the Statistical Analysis System (SAS Institute, 1991). Differences between means were tested at the $P < 0.05$ probability level.

Fourteen accessions of *L. fendleri* were planted for seed increase and evaluation at the USWCL, Phoenix, AZ. Available seed was limited so that seedlings were raised in the greenhouse before transplanting to the field to assure adequate plant establishment. Seeds were germinated in 300 × 300 × 50 mm flats with No. 1 Sunshine Mix Potting Soil under a mist bench. After the first true leaves appeared, seedlings were transplanted into single celled (50 × 50 × 50 mm) Speedling trays, where they remained for about six weeks until transplanting to the field in one plot per accession in December 1994. When plants started to flower, cages were placed over each plot to prevent cross-pollination among the different accessions. These cages were 1.3 × 2 × 2 m frames covered with a screen mesh. Common house flies (*Musca domestica*) were added to cages to facilitate pollination of the specific accessions. House flies were chosen over honeybees for pollination because of their low maintenance cost. Flies were added in the pupal stage in quantities of about 5000 per cage.

Six of the 14 accessions grown at the USWCL were from Arizona and eight from New Mexico (Table 3). The differences of the means for 1000 seed-weights and oil content between the original and increased USWCL accessions within Arizona and New Mexico were compared using paired comparisons with PROC MEANS (SAS Institute, 1991). Differences between the Arizona and New Mexico accessions, for 1000 seed-weights and oil content in Table 3 were tested by analysis of variance using the General Linear Model Procedure program (SAS Institute, 1991). The six original Arizona populations were compared to the eight original New Mexico populations. The same comparison was made using USWCL accessions for seed-weight and oil content. Differences between means were tested at the $P < 0.05$ probability level.

Table 1
Species of *Lesquerella* and *Physaria* collected from various states in 1993 and 1994. Numbers in parentheses reflect the number of populations collected

Arizona	New Mexico	Texas	Washington
L. cinerea (5) [a]	*L. gordonii* (2)	*L. densiflora* (2) [a]	
L. arizonica (3) [a]	*L. fendleri* (22)	*L. argyraea* (16)	*L. douglasii* (7) [a]
L. fendleri (22)	*L. ovalifolia* (1)	*L. fendleri* (41)	
L. gordonii (7)	*L. rectipes* (1) [a]	*L. grandiflora* (6)	
L. intermedia (4) [a]	*P. floribunda* (1)	*L. lasiocarpa* (7)	
L. kaibabensis (1) [a]		*L. lindheimeri* (4) [a]	
L. pinetorum (1)		*L. mcvaughiana* (1) [a]	
L. purpurea (2)		*L. recurvata* (7)	
L. rectipes (9) [a]		*L. sessilis* (2) [a]	
L. wardii (2) [a]			
P. newberryi (2) [a]			

[a] Species not previously represented in the NPGS.

3. Results and discussions

3.1. *Lesquerella fendleri*

The accessions collected in 1993 and 1994 are listed in Table 1. In most instances, natural populations of *L. fendleri* were found as single plants instead of dense stands. Associated plants with these populations included *Larrea*, *Prosopis*, *Gutierrezia*, *Opuntia*, *Yucca* and *Juniperus*. Plants were generally found growing on loose, loamy, limestone soils. Although limestone soils appear to be strongly associated with localities of this species, there were a few exceptions. Populations near the Arizona and New Mexico border, and two populations in Texas were growing on a loose red gravelly soil. Plants from the Arizona–New Mexico locality were abundant, and had a procumbent growth habit. Elevations of *L. fendleri* populations ranged between 240 and 1650 m.

Several populations were found in relatively dense natural stands in regions: east of Springerville, AZ, south of Tombstone, AZ, south of Lyman Lake, AZ (near St. Johns), west of Bylas, AZ, and Valley of the Fire, NM. Plants at the Valley of the Fire site were large and productive in seed set, which seemed rare for the high elevation (1600 m).

A few populations in southeastern Arizona had atypical growth habits. Near Sonoita, AZ, plants had cauline leaves that were broader and thicker than normal, with a procumbent growth habit. A collection found east of Tombstone, AZ had much larger leaves than the 'normal' wildtype. A population found in northwestern New Mexico near Red Rock, appeared to be growing as annuals.

In some cases, populations of *L. fendleri* were found growing sympatrically with other *Lesquerella* species and in one case with *Physaria*; *L. gordonii* in the Chiricahua Mountains, AZ, *L. ovalifolia* south of Santa Rosa, NM, *L. rectipes* near St. Johns, AZ, *L. purpurea* near Wilcox, AZ, *L. purpurea* west side of Dragoon Mountains, AZ, *L. argyraea* in Brewster County, TX, and *Physaria newberryi* west of Bylas, AZ. A putative natural hybrid with plant characteristics intermediate between *L. rectipes* and *L. fendleri* was found in northeastern Arizona. We have not yet been able to confirm this. No other introgressions between species were apparent in these other sympatric populations. Rollins and Shaw (1973) state that they have not verified any cases of interspecific hybridization in the field, except with the densipolic species found in Tennessee. In our breeding program, only rarely have we been successful obtaining interspecific hybrids under controlled crossing with these lesquerolic species.

Meiotic chromosome counts of *L. fendleri* plants collected in 1993 from Arizona and New Mexico were completed. All have been $n = 6$. Materials for chromosome counts were obtained from most of the Texas populations. However, these have not yet been completed. Rollins and Shaw (1973) reported a polyploid population of $n = 12$ in Texas. Since we

Table 2
Origin of original collection, collecion number, seed weight, seed oil content, and fatty acid composition of *Lesquerella fendleri* accessions

State	Collection number	Seed weight (g/1000)	Oil (%)	Fatty acid composition (%)						
				16:0	18:0	18:1	18:2	18:3	20:1-OH	20:2-OH
Arizona	1801	0.76	NA [a]	1.7	3.1	26.5	5.3	13.3	44.2	3.2
	1809	1.20	24.1	1.4	4.6	17.9	7.5	8.3	58.9	1.7
	1811	NA	NA	4.1	4.1	45.0	10.4	12.0	21.0	trace
	1817	0.97	NA	1.3	1.9	19.6	5.0	13.1	53.9	4.2
	1818	1.06	NA	1.4	2.6	20.7	5.9	14.5	49.6	4.2
	1819	1.14	19.0	2.3	2.7	25.4	7.0	13.6	44.0	2.6
	1826	1.02	24.2	1.4	2.2	20.6	5.6	13.7	51.0	3.7
	1847	0.60	NA	2.4	1.6	22.2	9.5	18.4	40.1	3.2
	1848	0.87	27.1	1.6	0.6	18.3	7.4	14.4	51.1	3.0
	1851	0.83	NA	1.4	1.9	19.0	6.0	14.9	51.1	4.1
	1852	0.66	22.3	1.5	2.3	22.5	5.6	13.5	48.6	3.6
	1854	0.66	NA	1.4	2.4	21.6	5.2	14.1	50.3	3.5
	1855	1.16	24.2	1.4	2.2	21.9	5.9	14.1	48.7	4.1
	1857	0.84	19.3	2.0	2.4	22.1	5.8	14.6	47.3	3.9
	1871	0.74	NA	1.5	1.6	17.6	7.8	17.4	47.9	3.7
	1874	0.60	NA	1.6	4.4	15.5	8.0	19.6	47.2	4.3
	1880	0.57	26.6	1.6	1.7	18.2	8.3	16.8	47.8	3.4
	1904	NA	NA	1.7	1.4	16.9	8.2	18.0	46.6	4.2
	1926	0.75	25.4	1.7	1.7	19.7	8.0	17.1	46.2	3.8
	1932	0.55	21.2	1.7	2.2	17.7	6.8	15.8	50.6	3.5
	1933	0.68	23.0	1.6	2.1	17.3	6.8	15.5	50.9	3.6
	1934	0.52	NA	1.6	2.3	17.9	6.6	16.2	49.8	3.9
	Mean ($\bar{x}$)	0.81	23.3	1.7	2.4	21.1	6.9	15.0	47.6	3.6
	C.V. [b]	26.8	11.5	34.3	40.8	28.5	20.6	16.4	14.7	17.2
New Mexico	1834	0.88	NA	1.3	2.0	18.6	5.0	16.9	48.9	5.6
	1835	NA	NA	2.0	2.1	22.0	8.6	15.2	45.4	2.7
	1836	0.56	27.9	1.6	1.9	19.4	9.3	14.9	47.8	2.9
	1838	0.52	NA	1.5	1.9	17.5	8.3	15.8	49.9	3.0
	1839	0.46	NA	1.4	2.0	17.2	8.2	15.9	50.2	3.2
	1840	0.64	NA	1.2	2.0	16.9	8.0	16.8	50.1	3.3
	1841	0.62	24.8	1.4	2.0	16.0	7.5	16.2	52.1	3.2
	1842	NA	NA	1.4	2.0	16.8	7.9	14.6	52.5	2.8
	1843	0.52	25.9	1.3	1.7	16.0	8.1	16.2	51.8	3.2
	1844	0.45	NA	1.5	1.9	17.9	8.4	16.0	49.2	3.2
	1845	0.60	20.5	1.8	2.0	17.7	7.7	18.0	47.2	3.9
	1846	NA	NA	2.4	2.3	25.0	9.1	16.4	37.2	3.6
	1887	0.68	28.9	1.5	1.7	17.0	7.1	15.5	51.1	4.1
	1889	0.39	29.1	1.5	1.5	17.2	6.7	18.7	47.7	4.9
	1906	NA	NA	1.8	1.7	19.3	8.8	16.7	46.9	3.2
	1907	NA	18.3	2.8	2.0	21.7	10.0	16.3	44.4	2.8
	1909	0.31	19.6	1.5	1.8	16.0	8.0	18.0	49.3	3.5
	1910	0.32	NA	1.7	2.0	19.6	8.4	17.6	45.8	3.4
	1912	0.76	23.5	1.5	1.9	18.6	7.4	17.0	48.3	3.2
	1913	NA	NA	2.3	2.7	19.3	10.9	18.4	43.0	3.3
	1919	0.73	23.4	1.5	1.5	20.3	7.6	19.4	43.8	3.6
	1920	0.67	27.1	1.7	1.7	17.6	6.8	19.4	45.2	5.3
	Mean ($\bar{x}$)	0.57	24.5	1.7	1.9	18.5	8.1	16.8	47.6	3.5
	C.V.	28.0	15.4	23.7	13.4	12.0	14.9	8.2	7.5	22.2

Table 2 (continued)

State	Collection number	Seed weight (g/1000)	Oil (%)	Fatty acid composition (%)						
				16:0	18:0	18:1	18:2	18:3	20:1-OH	20:2-OH
Texas	2226	NA	NA	1.6	2.8	26.9	9.1	11.5	43.4	2.5
	2255	0.62	22.5	1.8	1.8	19.5	6.5	16.3	48.8	3.7
	2256	0.49	22.8	1.6	1.7	20.3	6.8	15.2	50.4	3.2
	2257	0.47	26.2	1.4	1.7	18.4	6.7	14.9	52.1	3.2
	2258	NA	NA	1.7	1.8	18.3	6.5	16.1	49.8	4.2
	2259	0.44	NA	1.8	2.0	20.2	6.6	16.7	46.3	4.5
	2260	0.47	23.5	1.6	1.9	21.3	6.6	15.9	47.3	3.6
	2261	NA	NA	1.4	1.9	18.0	6.6	15.6	50.9	3.8
	2262	0.43	20.9	1.5	1.6	16.6	7.2	15.2	53.2	3.2
	2263	0.60	28.4	1.2	1.8	16.7	6.3	14.8	52.8	4.2
	2264	NA	NA	1.4	2.0	17.4	6.2	16.2	51.4	3.8
	2265	0.59	24.2	1.4	1.9	19.5	7.2	14.4	50.9	3.0
	2266	0.75	27.3	1.3	2.0	19.0	6.6	14.1	51.4	3.4
	2267	0.55	NA	1.4	1.8	16.6	6.9	15.3	52.3	3.7
	2268	0.66	26.1	1.4	2.0	20.7	7.2	13.7	49.6	3.1
	2269	0.49	22.0	1.4	2.1	17.8	6.1	16.6	49.7	4.7
	2270	0.63	25.5	1.5	2.1	21.7	7.6	13.7	48.4	2.8
	2272	NA	NA	2.8	2.6	22.0	7.9	15.4	46.3	3.0
	2273	0.66	28.7	1.5	1.7	19.0	8.5	13.1	50.9	2.7
	2276	0.63	17.3	1.8	2.2	21.1	6.6	13.9	48.5	3.9
	2277	0.55	20.9	1.5	2.2	17.8	7.8	14.1	51.7	3.1
	2278	0.60	NA	1.5	2.1	16.3	7.2	16.0	51.2	4.1
	2286	NA	NA	1.5	1.6	17.4	8.2	15.4	50.4	3.4
	2290	0.48	NA	1.3	1.8	16.8	7.5	16.0	51.2	3.6
	2291	0.51	22.9	1.6	1.9	20.2	7.4	14.4	49.8	2.8
	2292	0.76	NA	1.3	1.8	17.5	6.0	13.9	53.7	4.0
	2293	0.57	20.9	1.4	2.0	19.6	6.7	15.7	49.5	3.3
	2294	0.63	24.7	1.4	1.7	17.8	6.5	14.7	51.8	4.1
	2295	0.41	23.3	1.6	1.7	19.8	8.1	15.0	48.9	2.9
	2296	0.54	23.4	1.9	1.9	19.2	7.9	15.9	48.3	3.0
	2297	NA	NA	2.4	2.0	23.7	9.9	15.3	41.9	2.4
	2298	NA	NA	2.0	2.2	20.9	8.2	15.2	48.9	2.7
	2299	0.57	21.2	2.1	2.1	19.7	8.4	13.8	49.4	2.8
	2300	0.69	26.6	1.3	1.6	16.9	7.8	13.6	55.1	2.9
	2301	0.63	24.6	1.6	1.9	19.1	7.8	14.8	50.3	3.0
	2302	NA	22.5	1.6	1.7	22.1	6.6	15.5	46.3	4.8
	2303	NA	NA	1.3	1.7	17.3	7.1	14.1	53.3	3.0
	2304	0.65	24.7	1.3	1.7	18.0	6.6	14.0	54.0	3.5
	Mean ($\bar{x}$)	0.57	23.8	1.6	1.9	19.2	7.2	14.9	50.0	3.4
	C.V.	16.2	11.2	20.3	13.3	11.5	12.1	7.3	5.5	17.9
Mean ($\bar{x}$) [c]		0.65	23.8	1.6	2.0	19.5	7.4	15.4	48.7	3.5
C.V.		9.4	12.3	26.1	28.0	19.0	16.3	11.8	9.4	18.9

[a] Data not available.

[b] C.V. = coefficient of variation.

[c] Mean of collections from Arizona, New Mexico, and Texas.

collected near this reported area (Andrews County), some may be polyploids. Polyploidy found in other agricultural species has resulted in beneficial effects on important traits. It is possible that polyploidy in *Lesquerella* could produce material for further development by plant breeding.

Differences in 1000 seed-weights were found between accessions of *L. fendleri* collected in Arizona to those from New Mexico and Texas (Table 2). The 22 Arizona accessions produced significantly larger seed than the accessions from New Mexico and Texas. The t values for comparisons of means between Arizona and New Mexico, and Arizona and Texas were 2.91, $N = (21, 17)$, $P < 0.01$ and 3.44, $N = (21, 28)$, $P < 0.01$ respectively. This is also supported by the comparison of 14 accessions grown for seed increase in field plots at USWCL. The means of six accessions from Arizona were compared with an ANOVA test to the eight from New Mexico. Both the 1000 seed-weights and oil contents were significantly greater in the Arizona than the other accessions (F value of 8.12, $P < 0.05$ probability level, with 1 degree of freedom, Table 3).

The t value was not significant for the comparison of accessions from New Mexico and Texas for 1000 seed-weight. Also, differences between accessions from the three states for oil content and lesquerolic acid content were not significant (Table 2).

The variation found in 1000 seed-weights between the original collections and the USWCL cultivated plots could be due both to environmental differences on seed conditions and to open-pollination. However, overall comparison of averages indicates that more genetic variation for higher seed-weights exists in some of the Arizona populations. No significant differences were found in the average oil contents among the Arizona, New Mexico, and Texas populations (Table 2), or between selected original populations and cultivated accessions grown at the USWCL (Table 3).

Seed-weights of germplasm presently in our breeding program are similar to the measured weights obtained from the New Mexico and Texas collections, ca. 0.60 g/1000 seed (Dierig and Thompson, 1993; Thompson et al., 1989). However, it is possible that new collections from Arizona will introduce more diversity for seed size.

Table 3
Comparison of 1000 seed-weights and oil contents between seed from original collections and field cultivated plots grown at the U.S. Water Conservation Laboratory (USWCL) from 14 accessions of *L. fendleri*

Collection number	Seed weight (g/1000)		Oil content (%)	
	Original	USWCL	Original	USWCL
Arizona				
1848	0.87	0.78	27.1	25.5
1852	0.66	0.85	22.3	18.9
1855	1.16	0.82	24.2	22.3
1880	0.57	0.76	26.6	27.4
1926	0.75	0.66	25.4	26.9
1933	0.68	0.93	23.0	26.5
Mean [a]	0.78 a	0.80 a	24.8 a	24.6 a
C.V. [b]	27.0	11.4	7.8	13.5
New Mexico				
1838	0.52	0.57	NA [c]	22.0
1839	0.46	0.53	NA	22.0
1841	0.62	0.59	24.8	23.6
1845	0.60	0.56	20.5	23.1
1907	0.37	0.65	NA	24.6
1910	0.52	0.60	NA	25.1
1912	0.76	0.72	23.5	24.8
1920	0.67	0.80	27.1	22.4
Mean	0.56 b	0.62 b	24.0 a	23.5 a
C.V.	22.0	14.7	11.4	5.4

[a] Mean values in the same column followed by a different letter are statistically different, $P < 0.05$.
[b] C.V. = coefficient of variation.
[c] Data not available.

3.2. Other species of *Lesquerella* and *Physaria*

Nineteen other species of *Lesquerella* and two *Physaria* species were collected from Arizona, New Mexico, Texas and Washington (Tables 1 and 4). Significant differences were present for seed oil percentage, 1000 seed-weight, and fatty acid percentage differences both between the 19 species and among accessions within a species (Table 4). These characteristics have not previously been reported for *L.arizonica*, *L.cinerea*, *L. densiflora*, *L. douglasii*, *L. intermedia*, *L. rectipes*, *L. sessilis*, *L. wardii*, and *P. newberryi.*

L. gordonii and *L. rectipes* were collected in both Arizona and New Mexico. These were the only species common to both states, other than *L. fendleri*. *L. gordonii* appears similar to *L. fendleri*, but can be easily distinguished by differences in the trichomes and life history (annual vs. perennial). Both have the same chromosome number of $n = 6$. Based on the taxonomic treatment of the two species, we saw no introgression of these two. *L. gordonii* accessions had higher seed oil content, 1000 seed-weight, and in most cases, higher lesquerolic acid content ($C_{20:1\text{-}OH}$) compared to *L. fendleri* (Table 4). The oil content of

Table 4
Lesquerella and *Physaria* species, collection number, seed weight, seed oil content, and fatty acid composition

Species	Collection number	Seed weight (g/1000)	Oil (%)	Fatty acid composition (%)						
				16:0	18:0	18:1	18:2	18:3	20:1-OH	20:2-OH
L. argyraea	2210	0.45	NA [b]	2.0	2.5	16.9	11.8	5.4	58.4	trace
	2212	0.47	NA	NA	NA	NA	NA	NA	NA	NA
	2216	0.72	22.3	1.9	2.7	18.7	11.1	8.6	55.1	0.9
	2219	0.55	23.4	2.2	3.2	19.4	12.6	7.2	53.3	0.6
	2222	0.75	NA	2.1	3.1	18.2	14.3	6.2	54.9	trace
	2225	0.67	21.2	1.8	2.9	18.4	13.8	5.3	56.6	trace
	2239	NA	26.3	2.2	2.8	15.7	12.5	7.7	57.5	0.7
	2245	NA	25.9	1.7	2.6	19.9	11.5	7.5	54.5	0.7
	Mean ($\bar{x}$)	0.60	23.8	2.0	2.8	18.2	12.5	6.8	55.8	0.7
	C.V. [a]	21.8	9.3	9.8	9.1	8.0	9.4	18.1	3.2	17.4
L. arizonica	1893	1.02	NA	1.7	1.2	21.2	9.3	12.7	49.9	1.5
	1894	0.92	24.7	2.1	1.5	20.5	9.8	11.9	50.3	1.5
	1895	NA	NA	3.9	1.9	24.1	9.6	13.9	43.9	trace
	Mean ($\bar{x}$)	0.97	24.7	2.6	1.5	21.9	9.6	12.8	48.0	1.5
	C.V.	7.3	0.0	45.7	22.9	8.7	2.6	7.8	7.5	0.0
L. cinerea	1860	1.91	31.2	1.9	1.3	19.6	6.8	10.8	55.1	1.8
	1861	1.66	26.1	2.3	1.9	21.7	8.2	11.4	50.0	1.6
	1863	1.14	NA	2.1	1.6	24.8	9.4	10.7	46.9	1.2
	1869	1.50	NA	2.1	1.7	18.3	15.1	5.8	54.3	trace
	1931	1.91	29.5	2.6	1.8	20.7	8.7	10.7	51.4	1.3
	Mean ($\bar{x}$)	1.62	28.9	2.2	1.7	21.0	9.6	9.9	51.5	1.5
	C.V.	19.8	9.0	12.0	13.9	11.7	33.2	23.3	6.4	18.7
L. densiflora	2202	0.59	NA	1.3	1.7	13.7	7.9	8.0	64.8	1.1
L. douglasii	2400	NA	37.4	2.6	1.0	22.0	12.1	13.5	40.4	1.0
	2401	NA	25.5	1.4	0.7	15.8	9.7	14.6	47.0	1.8
	2402	NA	24.9	1.4	0.7	14.1	8.6	14.9	50.7	2.0
	2403	1.43	22.4	1.6	0.9	14.6	8.5	15.0	49.0	1.9
	2404	1.37	24.6	1.7	1.0	14.7	9.5	14.1	48.2	1.8
	2405	1.53	24.2	1.7	0.8	14.4	8.5	15.7	47.9	2.2
	2406	1.91	24.6	1.4	0.8	10.7	7.3	15.8	53.2	2.9
	Mean ($\bar{x}$)	1.56	26.2	1.7	0.8	15.2	9.2	14.8	48.1	1.9
	C.V.	15.6	19.1	25.0	15.9	22.3	16.4	5.6	8.2	29.7
L. gordonii	1800	0.72	29.6	1.8	1.5	21.8	5.9	7.5	57.3	trace
	1808	1.59	NA	2.0	1.7	21.5	9.4	14.7	45.2	2.7
	1830	0.70	28.1	1.8	1.7	21.5	7.2	6.3	57.7	1.0
	1831	0.78	NA	1.9	1.7	20.1	5.9	7.2	59.1	1.5
	1833	0.82	26.3	2.0	1.7	21.2	7.5	6.7	57.0	1.0
	1849	NA	NA	1.9	1.7	23.6	6.1	6.6	55.7	1.2
	1862	0.75	NA	2.2	2.0	22.8	6.5	7.2	54.7	1.4
	1883	0.97	30.9	1.7	1.7	22.0	6.4	7.4	56.9	1.4
	1885	0.66	31.7	2.0	1.7	22.9	6.6	7.9	54.9	1.2
	Mean ($\bar{x}$)	0.87	29.3	1.9	1.7	21.9	6.8	7.9	55.4	1.4
	C.V.	65.1	7.4	7.7	7.4	4.8	16.2	32.5	7.3	38.4
L. grandiflora	2243	0.59	NA	1.7	3.1	26.2	8.8	2.7	55.1	trace
	2246	NA	NA	1.6	3.2	29.9	7.4	1.8	53.4	trace
	2247	0.77	NA	1.4	3.3	27.6	7.3	1.9	55.8	trace
	Mean ($\bar{x}$)	0.68		1.6	3.2	27.9	7.8	2.1	54.8	
	C.V.	18.8		9.7	3.1	6.7	10.7	23.1	2.2	
L. intermedia	1879	0.93	17.3	2.7	1.6	24.6	8.3	15.1	43.1	2.0
	1882	0.76	24.3	2.3	1.7	23.2	7.5	13.5	47.0	2.0

Table 4 (continued)

Species	Collection number	Seed weight (g/1000)	Oil (%)	Fatty acid composition (%)						
				16:0	18:0	18:1	18:2	18:3	20:1-OH	20:2-OH
L. intermedia (continued)	1927	1.23	NA	2.0	1.6	18.6	8.6	11.5	53.6	1.7
	1930	0.99	30.0	2.1	1.2	20.1	6.8	14.2	51.0	2.3
	Mean ($\bar{x}$)	0.98	23.9	2.3	1.5	21.6	7.8	13.6	48.7	2.0
	C.V.	19.9	26.6	13.6	14.5	12.7	10.4	11.3	9.5	12.2
L. lasiocarpa	2217	0.43	NA	2.6	3.9	31.1	7.9	3.5	46.3	trace
	2228	0.55	19.5	1.8	3.7	28.8	7.2	2.8	51.8	trace
	Mean ($\bar{x}$)	0.49	19.5	2.2	3.8	30.0	7.6	3.2	49.1	
	C.V.	16.4	0.0	25.7	3.7	5.4	6.6	15.7	7.9	
L. lindheimeri	2232	0.78	NA	1.7	2.2	10.4	5.3	1.4	76.5	trace
L. mcvaughiana	2279	NA	NA	1.4	1.8	18.9	7.9	11.4	54.6	2.2
L. ovalifolia	1911	0.87	NA	2.0	1.3	18.3	10.4	15.1	48.3	2.0
L. pinetorum	1859	2.54	21.8	1.9	2.3	20.2	13.4	5.2	54.6	trace
L. purpurea	1802	2.29	NA	1.3	2.3	21.3	4.4	14.0	49.2	5.7
	1853	2.19	NA	1.4	1.9	15.8	8.8	7.1	61.5	0.9
	Mean ($\bar{x}$)	2.24		1.4	2.1	18.6	6.6	10.6	55.4	3.3
	C.V.	3.2		5.2	13.5	21.0	47.1	46.2	15.7	102.8
L. rectipes	1873	0.61	27.7	2.1	1.1	17.6	10.1	12.4	52.4	1.4
	1875	0.61	26.7	2.2	1.3	20.6	10.1	12.6	49.2	1.3
	1876	0.70	22.8	2.2	1.9	20.9	9.5	6.2	56.4	0.6
	1899	1.11	26.4	1.8	1.1	18.1	6.0	14.4	53.9	2.9
	1903	0.75	31.7	1.8	1.0	16.6	10.4	15.2	51.7	1.5
	1918	0.61	NA	1.7	1.2	19.1	9.3	13.5	51.0	1.9
	1922	0.45	26.7	2.0	1.5	20.4	8.5	14.3	48.8	1.7
	1923	0.96	34.3	1.5	1.0	19.4	7.6	12.7	53.2	2.2
	1924	0.84	32.2	1.8	1.1	20.8	9.2	13.5	49.5	1.6
	1925	0.40	NA	2.2	1.3	21.1	9.2	12.7	48.8	1.4
	Mean ($\bar{x}$)	0.70	28.6	1.9	1.3	19.5	9.0	12.8	51.5	1.7
	C.V.	31.2	13.3	12.7	22.1	8.1	14.8	19.4	4.9	36.7
L. recurvata	2203	0.46	19.7	1.8	2.2	17.3	10.1	4.5	61.9	trace
	2204	0.49	19.5	1.4	2.1	15.2	8.2	4.4	66.1	trace
	2205	NA	NA	1.6	2.3	18.8	10.1	4.1	60.7	trace
	2208	NA	NA	1.5	2.0	14.6	8.5	4.4	66.3	trace
	2249	0.45	NA	2.2	2.8	21.6	11.7	4.1	56.4	trace
	2250	0.58	22.4	1.3	1.9	12.0	6.1	5.8	69.7	0.9
	Mean ($\bar{x}$)	0.49	20.5	1.6	2.2	16.6	9.1	4.6	63.5	0.9
	C.V.	11.5	7.9	20.0	14.4	20.4	21.3	13.9	7.5	0.0
L. sessilis	2251	0.48	NA	1.6	1.8	13.0	6.6	4.2	69.8	trace
L. wardii	1901	1.03	21.6	1.8	1.3	15.3	12.1	12.5	52.9	1.2
	1902	1.24	NA	1.9	2.1	19.9	9.9	13.8	47.8	1.9
	1928	1.10	22.6	1.7	1.1	16.4	9.9	14.3	52.9	1.5
	Mean ($\bar{x}$)	1.12	22.1	1.8	1.5	17.2	10.6	13.5	51.2	1.5
	C.V.	9.5	3.2	5.6	35.3	14.0	11.9	6.9	5.7	22.9
P. floribunda	1917	1.8	26.1	1.4	1.5	15.2	11.7	12.1	55.1	1.5
P. newberryi	1896	6.2	32.4	1.8	1.3	23.6	7.8	15.0	46.1	2.7
	1929	4.5	29.3	2.2	1.5	27.7	7.9	14.3	41.5	2.5
	Mean ($\bar{x}$)	5.4	30.8	2.0	1.4	25.6	7.9	14.6	43.8	2.6
	C.V.	22.3	7.1	14.1	10.0	11.3	1.0	3.4	7.4	5.4

[a] C.V. = coefficient of variation.

[b] Data not available.

L. rectipes was higher than *L. fendleri*. However, seed yields of *L. fendleri* are greater and compensate for the lower oil content. Also, enough genetic variabilities are present in *L. fendleri* for these characters to be improved through breeding. An abundant population of *L. rectipes* was found south of Chinle, AZ. This species was found throughout Apache County, AZ. It was also collected in Rio Arriba County, NM, and Coconino County, AZ.

Populations of *L. arizonica*, *L. cinerea* and *L. intermedia* were all found in north-central and northwestern Arizona (Yavapai, Coconino and Mohave Counties). Some taxonomic problems were encountered in separating *L. wardii* and *L. kaibabensis*. The only clear distinction was in the flower color, with *L. kaibabensis* having white instead of yellow flowers. A population thought to be *L. kaibabensis* was found near the North Rim of the Grand Canyon, Arizona.

A population of *L. mcvaughiana*, also a white-flowered, perennial species, was collected in Pecos County, Texas at an elevation of 1430 m. Some associated plants at this locality included *Quercus*, *Pinus*, *Juniperus*, and *Nolina*. This was the only collection we found of this species, and was absent from the NPGS until now. Rollins and Shaw (1973) suggest that the species is limited in distribution, but abundant where it grows. The comparatively small number of populations of this species collected may be due to the relatively remote sites.

Several populations of *L. lasiocarpa* were collected in Texas and identified as variety *lasiocarpa*. Based on fruit shape and trichome differences, this species is divided into two subspecies (*lasiocarpa* and *berlandieri*) with different varieties (Rollins and Shaw, 1973). The species is known to occur in southern Texas and northern and northeastern Mexico. Mixed populations of *L. grandiflora* and *L. argyraea* were collected in Wilson County, Texas. One collection of *L. ovalifolia* var. *ovalifolia* was found in Sumner, NM. Only a small amount of seed were available. This species is not known to occur in Arizona.

The two *P. newberryi* populations collected from Arizona were very productive. *P. newberryi* had a much higher 1000 seed-weight, 5.4 g, compared to *P. floribunda* from New Mexico, which averaged 1.8 g (Table 4). Oil content was also higher although lesquerolic acid content was lower. Both of these species are perennial. This species may have potential for development as a hydroxy fatty acid source in cooler climates or in higher elevations than where *L. fendleri* is presently being developed.

The collections of *L.douglasii* were exclusively from Washington state. It is a perennial species, and found growing in gravelly or sandy soils. The localities from these seven collections were near river valleys. Associated plants included *Lupinus*, *Bromus*, *Chrysothamnus*, *Oenothera*, *Oryzopsis*, and *Agropyron*. In some cases, plants were found growing on very steep banks composed predominately of a sandy soil texture. Plants develop a long tap root as they mature. The vegetative portion of the plant may only contain a small rosette of leaves and still produce a large number (ca. 70–90) of infructescences. Most of the populations collected appeared very productive with respect to seed yields.

Based on field observations and seed evaluations, some of these species have potential for further agronomic development. *L.argyraea*, *L. douglasii*, *L. gordonii*, *L. grandiflora*, and *P. newberryi* had some or all populations of the individual species that were very productive in biomass and seed yield. Species such as *L. gordonii* have a wider range of distribution than *L. fendleri*, occurring throughout five southwestern states. Other species are more limited in distribution. In the United States, *L. argyraea* and *L. grandiflora* are only found in Texas, and *L. douglasii* primarily in Washington with a few localities in Oregon. (Note: the most recent locality information from Oregon we have seen at various herbaria was from the 1960's. Personal communication with plant taxonomists collecting in this area have indicated that many of these localities were inundated and are now lost because of the dams constructed on the Columbia River). *P. newberryi* ranges from north-central to eastern Arizona and adjacent New Mexico.

The populations of *L. argyraea* and *L. grandiflora* had similar productivity as the *L. fendleri* populations. The seed evaluations of *L. fendleri* in Table 2 compared to the *L. argyraea* populations in Table 4 are also very similar. Insufficient seed of *L. grandiflora* was available for oil content analysis. Previous reports (Hayes et al., 1995) indicate that oil contents are similar to *L. fendleri*. Although the averages of oil contents of *L. douglasii* listed in Table 4 are higher than those of *L. fendleri* in Table 2, certain populations are close to those values. In seed production *L. fendleri* is higher than *L. douglasii*. The oil content of one population of *L. douglasii* was the highest of any we collected. The lesquerolic acid content was lower on the average, although there appears to be variation for this fatty acid. The comparison of seed size between *L. fendleri* and *L. douglasii* does provide a good indication of the oil yield since the number of seeds per capsule from *L. fendleri* is three to four times greater than *L. douglasii* and most other species. This is also true with *P. newberryi*, which had the highest seed weights of any collections. Oil contents of *P. newberryi* were higher than of *L. fendleri*.

Seeds for the majority of accessions of *Lesquerella* and *Physaria* collected in 1993 and some from 1994 are being increased and undergoing evaluation with the goal of entering this new germplasm into the NPGS as quickly as possible.

Acknowledgements

We are grateful to ARS, USDA, Plant Exploration Office for partial funding of this project, Charlotte Christy, Plant Taxonomist, Arizona State University, for field collection in Texas, Dr. M. A. Foster, Texas A&M University, for assistance in collections from west Texas, and Joy Mastrogiuseppe, Plant Taxonomist, Pullman, WA, for field collections in Washington. Also to USDA, ARS, Plant Introduction Station, Pullman, WA and USDA, ARS, Carl Hayden Honey Bee Laboratory, Tucson, AZ for the use of frames and mesh screen for pollinations.

References

Abbott, T.P., Wu, Y.V., Carlson, K.D., Slodki, M. and Kleiman, R., 1994. Isolation and preliminary characterization of *Lesquerella fendleri* gums from seed, presscake, and defatted meal. J. Agric. Food Chem., 4: 1678–1685.

Dierig, D.A. and Thompson, A.E., 1993. *Vernonia* and *Lesquerella* potential for commercialization. In: J. Janick and J.E. Simon (Editors), New Crops. Proceedings of the Second National Symposium. New Crops: Exploration, Research, Commercialization. Indianapolis, Ind., October 6–9, 1991. John Wiley & Sons, Inc., New York, NY, pp. 362–367.

Dierig, D.A., Thompson, A.E. and Nakayama, F.S., 1993. Lesquerella commercialization efforts in the United States. Ind. Crops Prod., 1: 289–293.

Hayes, D.G., Kleiman, R. and Phillips, B.S., 1995. The triglyceride composition, structure, and presence of estolides in the oils of *Lesquerella* and other related species. J. Am. Oil Chem. Soc., 72: 559–569.

Miller, R.W., Van Etten, C.H. and Wolff, I.A., 1962. Amino acid composition of *Lesquerella* seed meals. J. Am. Oil Chem. Soc., 39: 115–117.

Roetheli, J.C., Carlson, K.D., Kleiman, R., Thompson, A.E., Dierig, D.A., Glaser, L.K., Blase, M.G. and Goodell, J., 1991. *Lesquerella* as a source of hydroxy fatty acids for industrial products, USDA–CSRS Office of Agricultural Materials. Growing Industrial Materials Series (unnumbered). Washington, DC.

Rollins, R.C., 1981. Studies in the genus *Physaria* (*Cruciferae*). Brittonia, 33: 332–341.

Rollins, R.C., 1993a. Historical perspectives on potential new crops: *Lesquerella* and *Guayuleas* examples. Symp. on New Industrial Crop Development, September 27, 1993. Annu. Meet. Assoc. Adv. Ind. Crops, New Orleans, LA (unpubl. abstract).

Rollins, R.C., 1993b. The Cruciferae of Continental North America, Stanford University Press, Stanford, CA.

Rollins, R.C. and Shaw, E.A., 1973. The genus *Lesquerella* (*Cruciferae*) in North America, Harvard University Press, Cambridge, MA.

SAS Institute, 1991. SAS/STAT User's Guide. Release 6.03 ed., SAS Institute Inc., Cary, NC.

Thompson, A.E. and Dierig, D.A., 1994. Initial selection and breeding of *Lesquerella fendleri*, a new industrial oilseed. Ind. Crops Prod., 2: 97–106.

Thompson, A.E., Dierig, D.A. and Nakayama, F.S., 1989. Yield potential of *Lesquerella fendleri* (Gray) Wats., a new desert plant resource for hydroxy fatty acids. J. Arid Environ., 16: 331–336.

Thompson, A.E., Dierig, D.A. and White, G.A., 1992. Use of plant introductions to develop new industrial crop cultivars. In: H.L. Shands and L.E. Weisner (Editors), Use of Plant Introductions in Cultivar Development. Part 2. Crop Sci. Soc. Am., Spec. Publ., 20: 9–48.